CAPACITANCE LEVEL MEASUREMENT

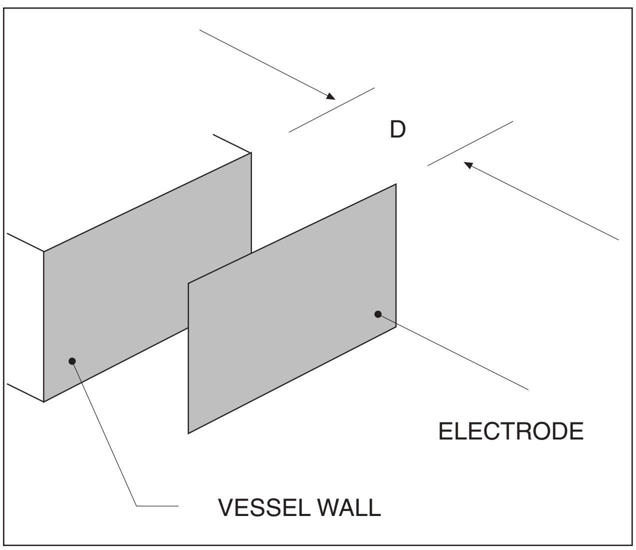
BASIC MEASURING PRINCIPLE

A capacitor is formed when a level sensing electrode is installed in a vessel. The metal rod of the electrode acts as one plate of the capacitor and the tank wall (or reference electrode in a non-metallic vessel) acts as the other plate. As level rises, the air or gas normally surrounding the electrode is displaced by material having a different dielectric constant. A change in the value of the capacitor takes place because the dielectric between the plates has changed. RF (radio frequency) capacitance instruments detect this change and convert it into a relay actuation or a proportional output signal. The capacitance relationship is illustrated with the following equation:

$$C = 0.225\, K \left(\frac{A}{D}\right)$$

where:

- C = Capacitance in picoFarads
- K = Dielectric constant of material
- A = Area of plates in square inches
- D = Distance between the plates in inches



The dielectric constant is a numerical value on a scale of 1 to 100 which relates to the ability of the dielectric (material between the plates) to store an electrostatic charge. The dielectric constant of a material is determined in an actual test cell. Values for many materials are published by the National Institute of Standards and Technology.

In actual practice, capacitance change is produced in different ways depending on the material being measured and the level electrode selection. However, the basic principle always applies. If a higher dielectric material replaces a lower one, the total capacitance output of the system will increase. If the electrode is made larger (effectively increasing the surface area) the capacitance output increases; if the distance between measuring electrode and reference decreases, then the capacitance output decreases.

Level measurement can be organized into three basic categories: the measurement of non-conductive materials, conductive materials and proximity or non-contacting measurement. While the following explanations oversimplify the measurement, they provide the basics that must be used to properly specify a capacitance measurement system.

- **Non-Conductive Materials**—As previously stated, capacitance changes as material comes between the plates of the capacitor. For example, suppose the sensor and the metal wall are measuring the increasing level of a non-conductive hydrocarbon. Figure 1 depicts a typical system.

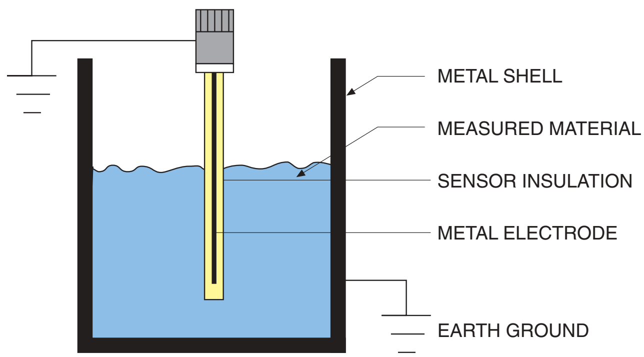


Figure 1- Capacitive Measurement In Non-Conductive Media

While the actual capacitive equation is very complex, it can be approximated for the above example as follows:

$$C = \frac{0.225\,(K_{air} \times A_{air})}{D_{air}} + \frac{0.225\,(K_{material} \times A_{material})}{D_{material}}$$

Since the electrode and tank wall are fixed in place, the distance between them will not vary. Similarly, the dielectric of air and of the measured material remain constant (air is 1 and the hydrocarbon is 10). Consequently, the capacitance output of the system example can be reduced to this very basic equation:

$$C = (1 \times A_{air}) + (10 \times A_{material})$$

As this equation demonstrates, the more material in the tank, the higher the capacitance output will be. The capacitance is directly proportional to the level of the measured material.

- **Conductive Materials**—The same logic for non-conductive materials applies for conductive materials, except that conductive material acts as the ground plate of the capacitor, rather than the tank wall. This changes the distance aspect of the equation, whereby the output would be comparatively higher than for a non-conductive material. However, it still remains fixed; therefore, as level rises on the vertically mounted sensor, the output increases proportionally.

NOTE: A material is considered conductive when it has a conductivity value of greater than 10 microSiemens/cm.

> **WARNING**
> A non-insulated level sensing electrode must NOT come in contact with conductive material, in which case the sensor will act like a switch.

- **Proximity (non-contacting) Measurements**—The level sensing electrode is normally a flat plate mounted parallel to the surface of the material. The material, if conductive, acts as the ground plate of the capacitor. As level rises to the sensor plate, the effective distance between plates is decreased, thus causing an increase in capacitance. In non-conductive materials, the vessel acts as the ground plate and the mass of material between the plates is the variable. In the measurement of non-conductive and conductive materials, the area changes and the distance is fixed. Proximity level measurement is exactly the opposite in that the area is fixed, but distance varies.

  Proximity level measurement does not produce a linear output and can only be used when the level varies by several inches.

Some typical level sensor installations for measuring conductive and non-conductive materials and for proximity level measurement are shown in Figures 2 and 3.

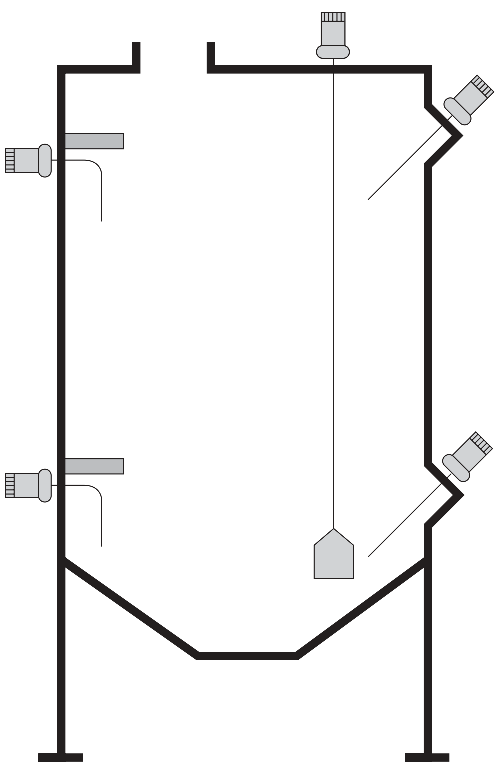


Figure 2

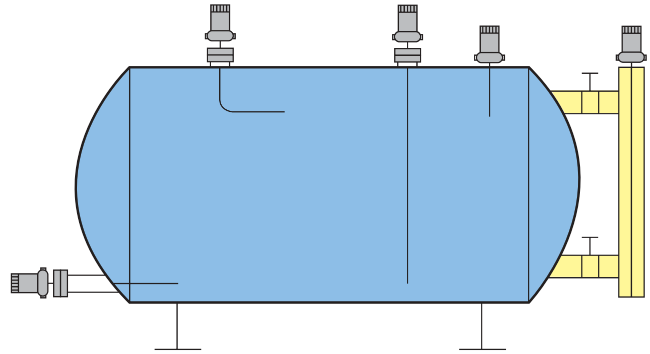


Figure 3

APPLICATIONS

Applications for RF point level controls and analog transmitters/controllers are widespread. Granular applications range from light powders to heavy aggregates. Applications in liquids, slurries and pastes are commonplace. Capacitance level can also be used to detect the interface between two immiscible materials.

Selecting the proper level sensing electrode and installing it in the proper location are important factors that contribute to the success of any application. A thorough understanding of these factors is required.

- *Electrode Selection*—The electrode is the primary measuring element and must be capable of producing sufficient capacitance change as it becomes submerged in the measured material. Several electrode types are offered, each having specific design characteristics. Capacitance (per foot of submersion) vs. dielectric constant curves are published for each type as installed in various size vessels. For non-conductive materials, these curves are non-linear. Figure 4 shows a typical set of curves. As the size of the tank gets smaller, the capacitance per foot of submersion increases. A conductive material essentially makes the tank be the size of the electrode insulation.

  Note: Continuous level transmitter applications require a minimum span of 10.0 pF and a maximum span of 10,000 pF.

  In this case, the saturation capacitance is used. Table A lists basic capacitance values for different electrodes and tank sizes.

CAPACITANCE LEVEL PROBE SELECTION GUIDE

The simplest applications are clean, non-coating conductive liquids (such as many water-based liquids) in metallic tanks. An insulated probe must be used, and the fluid is grounded to the probe through the tank. The capacitance change per foot = the saturation capacitance.

Clean, non-coating conductive liquids (such as many water-based liquids) in non-metallic tanks require the use of a concentric probe. The capacitance change per foot = the saturation capacitance. See application note “RF Level Measurement in Lined Vessels with Grounded Shell” for details on lined or coated metallic tank applications. Clean, non-coating non-conductive liquids (such as many hydrocarbons) in non-metallic tanks require the use of a concentric probe. The

GENERAL PURPOSE PROBE - TFE INSULATED

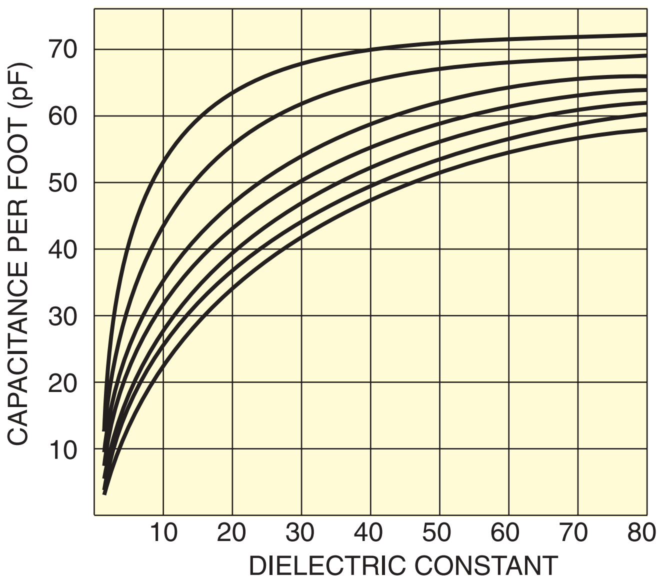


Figure 4

capacitance change per foot depends upon the dielectric constant of the material.

Clean, non-coating non-conductive liquids (such as many hydrocarbons) in metallic tanks require special consideration. A bare (un-insulated) probe can be used, but one must insure that the probe does not come in contact with any conductive liquid that may contaminate the non-conductive liquid (such as water in oil). If this occurs, the output will be driven to full scale, regardless of the actual level in the tank. Note that an insulated probe can also be used. The probe's metal fitting must be grounded to the metal tank wall, and the distance from the tank wall to the probe must be constant along the entire length of the probe, to provide a linear change in analog output per change in fluid height. If this is not the case (i.e. the tank is "irregular" in shape), or if the tank is greater than 15 ft in diameter, a concentric probe should be used. The capacitance change per foot depends upon the dielectric constant of the material, as well as the tank diameter (tank diameter does NOT effect the concentric probe).

After making a preliminary probe selection based upon the above considerations, it is important to insure that the capacitance of the probe selected meets the following limitations: the capacitance at zero level in the tank is less than 500 pFd, and the maximum capacitance at full span level is more than 10 pFd but less than 10,000 pFd. Also, the zero to span ratio must not exceed 10 to 1. That is, if the zero pf value is 200, the span must be at least 20 pf.

THIS IS CALCULATED AS FOLLOWS:

For the LV5100 probe, TFE insulated, in a 24" tank, with a dielectric = 2 (air has a much lower dielectric, so this calculation is very conservative), the pFd per foot is 6 pFd. The maximum length of this probe is 12 ft, so that the maximum probe capacitance in the open air is = (6 x 12) + (42 pFd - gland capacitance) = 114 pFd, which is less than 500 pFd. Note that no probe has greater than 50 pFd gland capacitance.

Helpful Hint

500 pFd can only be exceeded with an LV5300 probe of greater than 25 ft length, or greater than 9 ft length in the LV5102 PVDF insulated heavy duty probe, or greater than 9½ ft length in the polyethylene insulated heavy duty probe.

For the LV5100 probe, TFE insulated, in a 24" tank, with a dielectric = 2 (this is a typical value for hydrocarbons) the pFd per foot is 6 pFd. The maximum length of this probe is 12 ft, so that the maximum span capacitance is = (6 x 12) + (0 pFd - gland capacitance is not added to the span) = 72 pFd, which is greater than 10 pFd and less than 10,000 pFd. Note that if the probe were only 1 ft long, that the maximum span capacitance would be only 6 pFd, which is less than the required 10 pFd.

Helpful Hints

- 10,000 pFd can only be exceeded with an LV5300 probe of greater than 39 ft length, or greater than 10 ft length in the LV5202 or LV5212 PVDF insulated enhanced performance probe with a conductive liquid.
- To have less than 10 pFd span, one must have a span of less than 1 ft for non-conductive liquid with dielectric less than 20 and in a tank greater than 1" diameter.
- Note that the "Saturation Capacitance" values should be used when the liquid is conductive (i.e. above 20 microsiemens/cm), such as water-based fluids that are not ultra-pure or distilled or deionized.

Field Calibration Required:

Capacitive level transmitters must always be calibrated for zero and span in the field. The concentric probe can be tested in a bucket or small tank of the liquid to be measured; all other probes must be calibrated after final installation by changing the material level and adjusting the zero and span pots.

Unlined Plastic Tanks:

Due to the low gains in large tanks, concentric probes are recommended for unlined plastic tanks to minimize this effect and to provide a ground reference.

Large Diameter Metal Tanks for Low Dielectric Fluids (such as Hydrocarbons)

Due to the low gains in large tanks, concentric probes are recommended for metal tanks greater than 20 foot diameter used to measure low dielectric fluids (such as hydrocarbons). Also, if concentric probe is impractical, mount closer to tank wall if possible.

- *Electrode Location*—Mounting positions should be carefully considered. They must be clear of the inflow of material as impingement during a filling cycle can cause serious fluctuations in the capacitance generated. Side mounted electrodes with point level controls are typically mounted at a downward angle to allow the measured material to drain or fall from the electrode surface.
  Electrodes mounted in nozzles should contain a metal "sheath" extending a few inches past the nozzle length. The sheath renders that part of the

K

electrode insensitive to capacitance change, and therefore, ignores the material which may build up in the nozzle.

NOTE: In addition to the electrode selection and location factors, there are other considerations which can have a significant impact on the measurement. See "Special Considerations" below.

> **WARNING**
>
> Vertically mounted electrodes must be clear of agitators and other obstructions and far enough from the vessel wall to prevent "bridging" of material between the electrode and the vessel wall.

CONTINUOUS LEVEL MEASUREMENT

Various methods are used to minimize the coating error. These include proper electrode selection, higher frequency measurements, phase shifting and conductive component subtraction circuits.

Coating error is illustrated by the diagram shown in Figure 5. The submerged portion of the electrode generates nearly a pure capacitive susceptance. Since the electrode is insulated, a conductive component is virtually non-existent. However, the upper section of the electrode, coated with conductive material, generates an error signal consisting of a capacitive susceptance and a conductive component. The result is an admittance component which is 45° out of phase with the main level signal. A study of transmission line theory is required to prove this phenomenon. An equivalent circuit for the coated section is shown as a ladder network producing the phase shifted error signal.

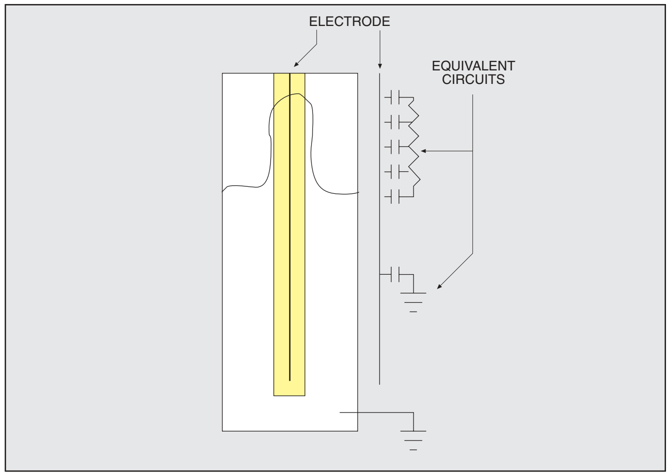


Figure 5

Special Considerations

1. *Temperature*—The dielectric constant of some materials varies with temperature which affects the capacitance measured by the electrode. Generally, materials with a higher dielectric constant are less affected by temperature variation. The temperature effect is usually given in the tables of dielectric constants.

   WARNING

   The effect of changing temperature and changing dielectric can not be quantified; if temperature or dielectric constant change, it is recommended that the level transmitter be calibrated at each temperature and dielectric constant value to quantify the effect of the changes.

2. *Moisture Content*—The dielectric constant of granular materials changes with changing moisture content. This variation can cause significant measurement errors, so each application must be carefully examined. Accuracy requirements determine the amount of moisture change that is tolerable.

   WARNING

   The effect of changing moisture content can not be quantified; if moisture content changes, it is recommended that the level transmitter be calibrated at each moisture level value to quantify the effect of the changes. In addition, the LV5000 series level transmitter should NOT be used with hygroscopic materials (i.e. those materials that absorb moisture from the atmosphere).

3. *Static Change*—Air-conveyed, non-conductive granular materials such as nylon pellets build up a static charge on the electrode which can damage the electronic components in the measuring instruments.

   WARNING

   The LV5000 series level transmitter should NOT be used with materials that could build up static charges.

4. *Composition*—The dielectric constant of the measured material must remain constant throughout its volume. Mixing materials with different dielectric constants in varying ratios will change the overall dielectric constant and the resultant capacitance generated. Solutions having a high dielectric constant are less affected due to the saturation capacitance of the electrode system. See capacitance vs. dielectric constant curve in Figure 4.

   WARNING

   The LV5000 series level transmitter should NOT be used with materials of varying compositions.

5. *Conductivity*—Large variations in the conductivity of the measured material can introduce measurement error. The proper electrode selection can minimize this effect. A thick wall electrode insulation is recommended in this case.

   WARNING

   The effect of changing conductivity can not be quantified; if conductivity changes, it is recommended that the level transmitter be calibrated at each conductivity value to quantify the effect of the changes.

6. *Material Buildup*—The most devastating effect on the accuracy of RF capacitive measurements is caused by the buildup of conductive material on the electrode surface. Non-conductive buildup is not as serious since it only represents a small part of the total capacitance. Latex, carbon black, and fine metal powders are examples of materials that produce conductive coatings.

One means of cancelling the error signal is to measure the conductive component (c) shown in Figure 6, Method A. Since the 45° relationship exists, the capacitive error component (e) is the same magnitude and can be subtracted from the total output signal, thereby effectively canceling the error signal.

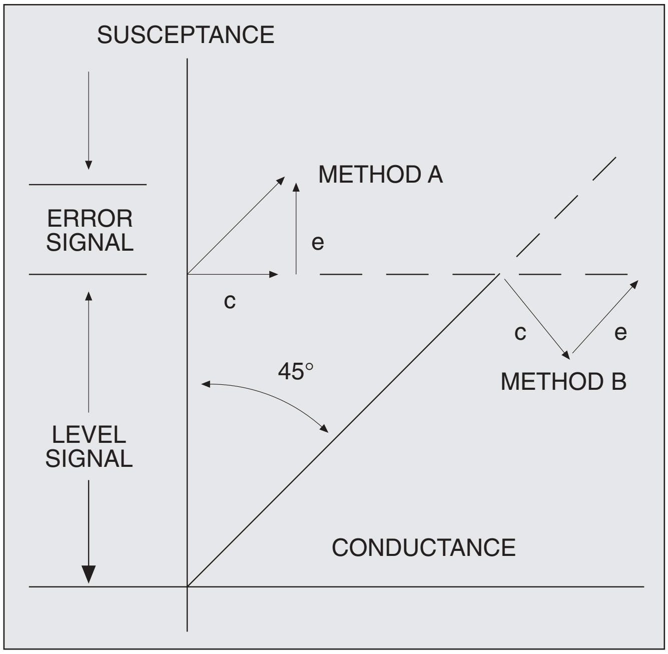
Another cancellation method is to introduce a 45° phase shift to the entire measurement as shown in Figure 7, Method B. This automatically cancels the coating error portion because the conductance component (c) still has the same magnitude as the error component (e), resulting in the appropriate level signal. Instruments which incorporate these techniques are known as "admittance" types.

The coating error can also be reduced by increasing the capacitive susceptance. This is accomplished by increasing the frequency of measurement and/or decreasing the electrode insulation wall thickness.

It should be noted that any of these techniques cannot perfectly cancel the coating effect, but each tends to reduce the error.

WARNING

For all of the preceding reasons, RF continuous level instrumentation is not used in inventory control applications.



Admittance Vector Diagram
Figure 6

These are process control devices which require careful evaluation of the listed considerations to provide satisfactory results.

Table A—Capacitance Values (pF per foot)										
	Non-Conductive Materials/Tank Diameter									Conductive Material (Saturation Capacitance)
	Dielectric = 2			Dielectric = 20			Dielectric = 80			
Type of Sensor	1"	24"	96"	1"	24"	96"	1"	24"	96"	
General Purpose (LV5000 Series):										
TFE Teflon® Insulated	15 pF	4 pF	2 pF	63 pF	39 pF	34 pF	73 pF	62 pF	58 pF	76 pF
Polyethylene Insulated	16 pF	6 pF	3 pF	123 pF	57 pF	46 pF	167 pF	120 pF	117 pF	189 pF
PVDF Insulated	18 pF	7 pF	4 pF	178 pF	68 pF	50 pF	280 pF	169 pF	142 pF	350 pF
Heavy Duty (LV5100 Series):										
TFE Insulated	35 pF	6 pF	4 pF	74 pF	44 pF	36 pF	78 pF	66 pF	62 pF	79 pF
Polyethylene Insulated	48 pF	5 pF	3 pF	172 pF	66 pF	52 pF	190 pF	131 pF	116 pF	198 pF
PVDF Insulated	52 pF	8 pF	5 pF	282 pF	78 pF	58 pF	340 pF	190 pF	158 pF	365 pF
Enhanced Performance (LV5200 Series):										
PFA Teflon® Insulated	23 pF	5 pF	3 pF	147 pF	160 pF	48 pF	187 pF	128 pF	114 pF	207 pF
Polyethylene Insulated	22 pF	8 pF	5 pF	260 pF	78 pF	58 pF	410 pF	210 pF	165 pF	518 pF
PVDF Insulated	25 pF	10 pF	8 pF	330 pF	80 pF	60 pF	640 pF	260 pF	205 pF	950 pF
Flexible Cable (LV5300 Series):										
PFA Teflon® Insulated	14 pF	5 pF	3 pF	50 pF	34 pF	30 pF	57 pF	49 pF	30 pF	58 pF
Polyethylene Insulated	17 pF	5 pF	3 pF	103 pF	52 pF	43 pF	132 pF	101 pF	91 pF	146 pF
PVDF Insulated	18 pF	5 pF	3 pF	154 pF	62 pF	48 pF	222 pF	145 pF	128 pF	254 pF
Concentric (LV 5500 Series)										
Teflon®		25			67			75		76
Polyethylene		25			142			175		189
Kynar		35			220			305		350

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